Horizontal Variability of Ocean Skin Temperature from Airborne Infrared Imagery

Christopher J. Zappa
Woods Hole Oceanographic Institution
WHOI Mailstop #12
Woods Hole, MA 02543
Phone: (508) 289-2587 fax: (508) 457-2194 email: czappa@whoi.edu

James B. Edson
Woods Hole Oceanographic Institution
WHOI Mailstop #12
Woods Hole, MA 02543
Phone: (508) 289-2935 fax: (508) 457-2194 email: jedson@whoi.edu

Award Number: N00014-01-1-0081

LONG-TERM GOALS

The long-term goal is to understand the mechanisms that produce spatial variability over a wide range of scales in ocean surface skin temperature under low wind conditions.

OBJECTIVES

The first objective is to use an airborne infrared imager to produce both overview maps and high-resolution time series of thermal variability over the CBLAST study area. The second objective is to combine these data with measurements by other investigators to determine the extent to which horizontal variability in surface temperature is related to atmospheric and sub-surface phenomena.

APPROACH

The approach is to make airborne measurements of horizontal variability of ocean surface skin temperature during the CBLAST-LOW experiments using two complementary infrared (IR) sensors. An IR imaging system will provide high spatial and temporal resolution while a narrow field-of-view (FOV) radiometer system will provide calibrated surface temperature. The IR imager system will use up- and down-looking cameras in order to discriminate between real skin temperature variations and apparent variations caused by reflection from clouds. The high spatial coverage and fine spatial and temperature resolution of our systems will allow us to examine spatial scales in skin temperature from processes that span the atmospheric boundary layer of O(1km) down to wave-related processes O(1m). We will produce synoptic maps of temperature covering the CBLAST-LOW region at moderate altitude as well as observations of fine-scale structures. During flights we will transect between the tower and the offshore mooring sites at altitudes of 300 m to 1000 m. This will provide the opportunity to utilize the tower and offshore array data sets as well as directly compare sea-surface signatures with the oceanic and atmospheric boundary layer processes and fluxes. For the pilot experiment in 2001, we made sea surface measurements with a single Amber Radiance HS shortwave imager (256 x 256 pixels), a Pulnix digital video camera, and a Heimann KT-15 radiometer. For the 2nd experiment in August/September of 2002, we made measurements of the sea surface and the sky

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Horizontal Variability of Ocean Skin Temperature from Airborne Infrared Imagery**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Woods Hole Oceanographic Institution,,WHOI Mailstop #12,,Woods Hole,,MA,02543**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long-term goal is to understand the mechanisms that produce spatial variability over a wide range of scales in ocean surface skin temperature under low wind conditions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

with down- and up-looking AIM model 640Q longwave IR imagers (512 x 640 pixels) and Heimann KT-15 radiometers. A Pulnix digital video camera was implemented to characterize the sea surface condition.

WORK COMPLETED

We analyzed data taken during the CBLAST pilot experiment that occurred in July/August of 2001. We participated in the 2nd CBLAST experiment in August/September of 2002 by mounting our newly-developed dual IR imager system on a Cessna Skymaster aircraft. Prior to the experiment, the primary effort was the development of a data acquisition system that would meet the weight and space requirements of the Cessna Skymaster aircraft. The data have been cataloged and we are beginning to survey them for interesting features.

RESULTS

During the pilot experiment, the imager operated in the short wavelength IR band and therefore is susceptible to solar reflection during the daytime. Therefore, we focused on the measurements made during flights before sunrise or after sunset and at high altitude.

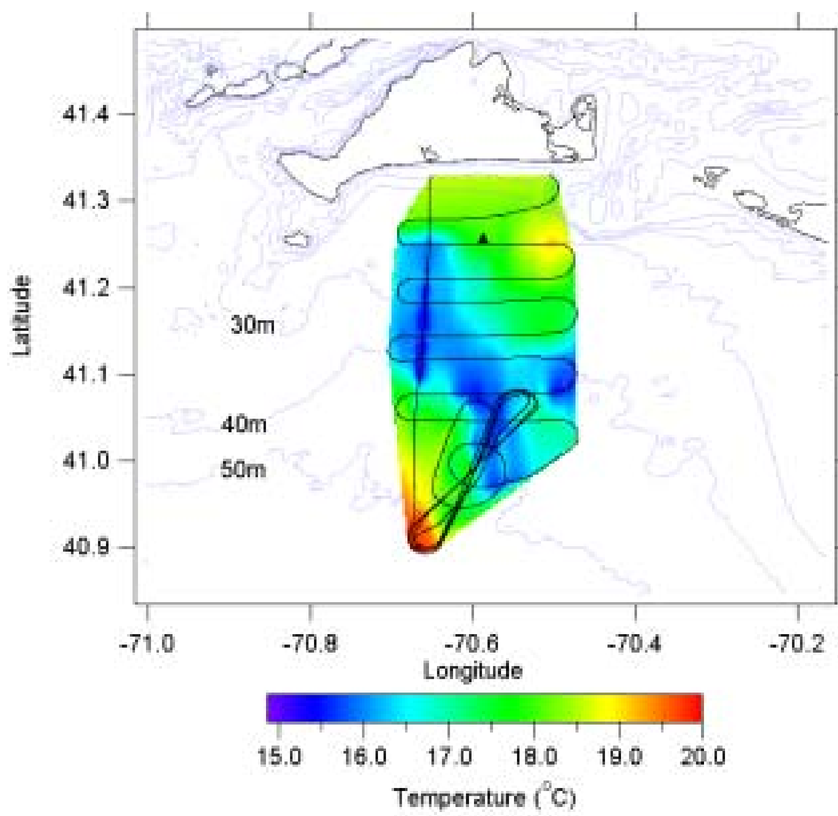
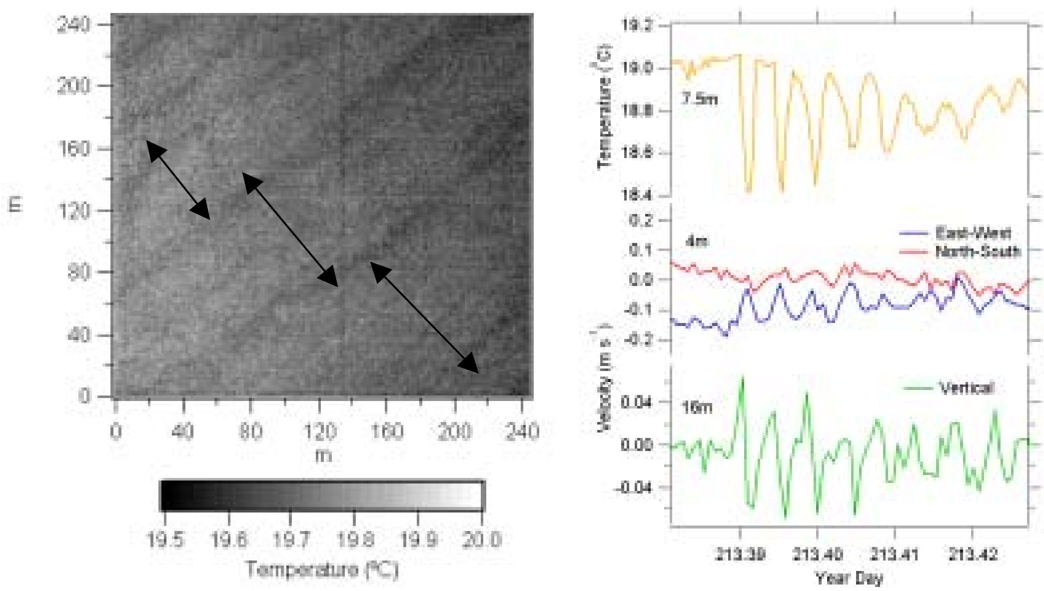


Figure 1. Map of sea surface temperature measurements produced using the low-noise, high resolution data from the imager (calibrated against the radiometer). The black trace is the LongEZ flight track. The scale of the temperature features is on the order of tens of kilometers and on the order of 3 to 5°C.

Figure 1 shows a map of sea surface temperature produced using the low-noise, high-resolution data from the Amber Radiance HS infrared imager. These data were taken at dawn on 7-31-01 from 0930 - 1200 hours UTC (7-31-01, 0530 – 0800 local) from an altitude of 390 m. The wind speed ranged from 4 to 6 m s^{-1} and the direction was from the NE. At this altitude, the spatial resolution in an image is 1 m and the diameter of the surface spot viewed by the narrow FOV radiometer is 43 m. The technique for obtaining high spatial resolution and low noise temperature measurements is to operate the imager at a fast frame rate and then obtain a point measurement by taking the average of a portion of the image corresponding to less than the radiometer FOV. This technique provides much lower noise equivalent temperatures of less than 0.1 °C compared to 0.5 °C for radiometers when operated at a sample rate of 30 Hz. However, the Heimann radiometer provided a more accurate measurement than the Amber imager and was used to calibrate the imager measurements. These results indicate that our technique to obtain high resolution, low noise temperature measurements using an airborne imager will yield the desired result. The example in Figure 1 is characteristic of temperature maps of the CBLAST-LOW site during the 2001 pilot study and shows the large-scale spatial variability to be on the of *O*(10km) and temperature variability of roughly 3 to 5°C.



(a) (b)

Figure 2. (a) Example of fine-scale IR imagery as observed from the aircraft taken on 8-1-01. It shows banding features observed during the passage of internal waves through the CBLAST-LOW site south of Martha's Vineyard for low wind speed conditions (North is up). The arrows highlight the spacing between dark bands corresponding to cooler temperature. The spatial scale of the banding features ranges from 50 to 100m. (b) Temperature and velocity time series measured at the SECNAV buoy site showing the structures characteristic of the passage of internal waves.

We observed fine-scale features within the IR imagery under low wind speed conditions. Figure 2a depicts an example of the infrared signature that is produced during the passage of a discrete internal wave packet at the SECNAV buoy site. These data were taken at dawn on 8-1-01 from 1000 - 1230 hours UTC (8-1-01, 0600 – 0830 local) from an altitude of 390 m. The wind speed ranged from 4 to 6 m s^{-1} and the direction was from the NW. Each image is roughly 245 m x 245 m and the axis scales correspond to the spatial scale in meters. The infrared image in Figure 2a shows distinctive banding streaks of various scales that are aligned with the coastline. Lighter shades of gray are warmer temperatures. These long parallel features exhibit an alternating thin cool region (roughly 5 to 10 m) followed by a broad warm region (roughly 40 to 80 m). These band-like features are likely the surface manifestation of internal waves propagating shoreward. In Figure 2b, a single thermistor from the buoy subsurface vertical array shows the evolution of a propagating internal wave train with peak to trough amplitude swings of nearly 2°C. Using a two-layer stratified model corrected for currents, the wavelength of the internal waves was found to be comparable to the spatial scale of the features observed in the IR imagery. Near-surface current meters demonstrate the existence of coherent variability in velocity, as depicted in Figure 2b, indicating convergent/divergent zones that modulate the wave field and/or accumulate surfactant. Since the near-surface ocean is well-mixed down to 4 m, the modulation of the aqueous thermal boundary layer (TBL) of order 0.5°C suggests that the internal waves modulate the TBL by modulating the surface flow field. To the best of our knowledge, these are the first such digital airborne IR images accompanied by high-quality in-situ data that show the direct modulation of the aqueous thermal boundary layer by internal waves.

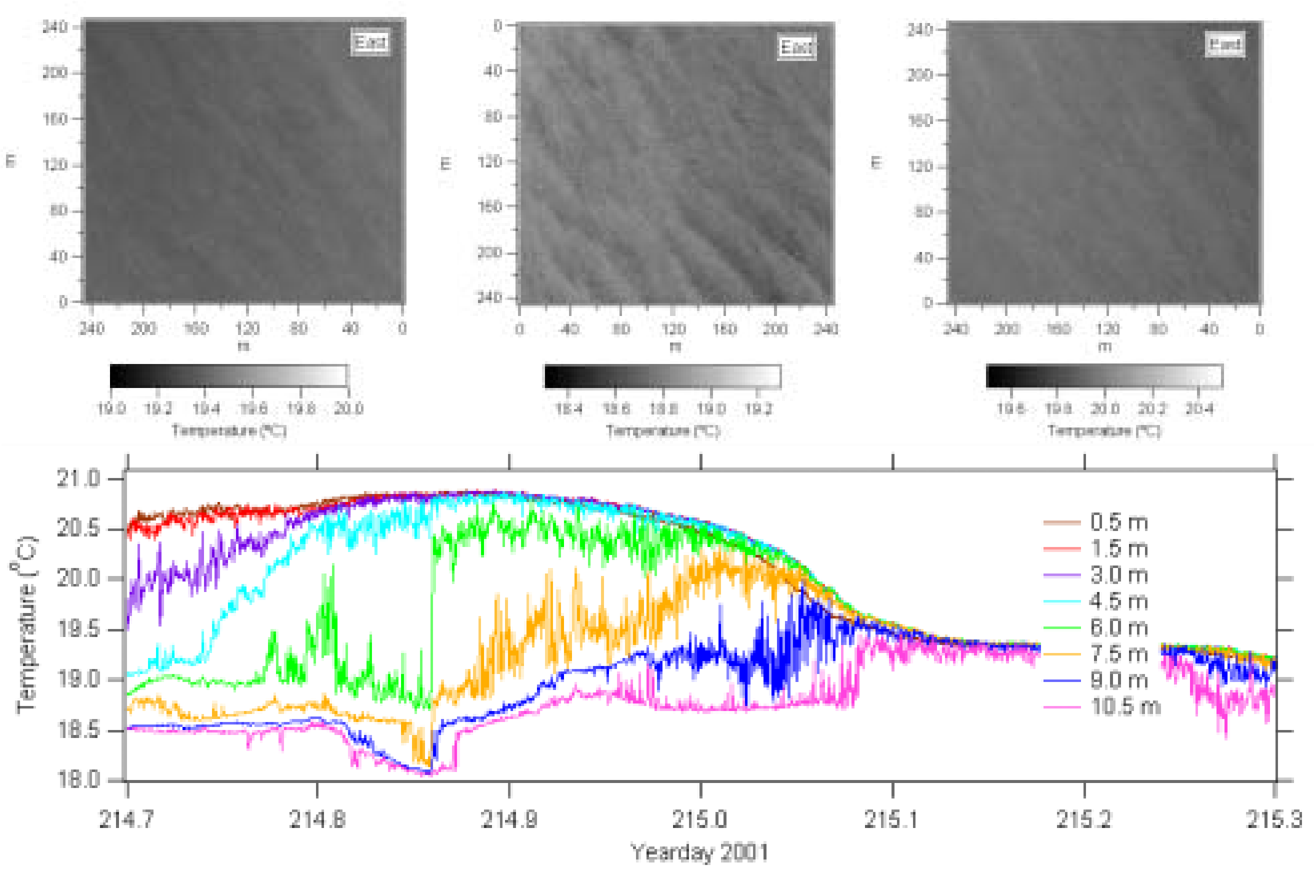


Figure 3. Infrared images (top) showing the evolution of coherent ramp-like features observed on 8-3-01 during a period of stratification breakdown as depicted in the times series of temperature (bottom). The look direction is noted at the top of the image and the black arrow shows the wind direction was from the NW.

We also observed the evolution of fine-scale features within the IR imagery during a transitional wind speed period. Figure 3 shows a comparison of IR imagery (top) taken before, during, and after the stratification breakdown that is demonstrated in the temperature time series (bottom) from the vertical thermistor array buoy. These data were taken at night on 8-3-01 from about 0100 - 0300 hours UTC (8-2-01, 2100 – 2300 local) from an altitude of 390 m. The wind speed was steadily increasing from 5 to 8 m s^{-1} and the direction was from the NW. The 1st (Yearday 214.7) image demonstrates a roughly uniform region of sea surface temperature and was taken when the upper ocean was well stratified. As the wind-speed picked up, the 2nd (Yearday 215.0) image shows distinctive successive ramping features that steadily increase in temperature and abruptly drop by up to 0.5°C. These coincide with the near-surface layer mixing down to roughly 6 m. The spatial scale of these coherent ramps structures is roughly 10 m and is comparable to the depth of mixing, and the structures are oriented perpendicular to the wind. The 3rd (Yearday 215.2) image in Figure 3 (top) again demonstrates a roughly uniform region of sea surface temperature and was taken when the upper ocean was well mixed down to at least 10 m. These coherent ramp structures suggest a potential mechanism in the near-surface layer that leads to the stratification breakdown under conditions when the turbulence transitions from a buoyancy- to a shear-driven state.

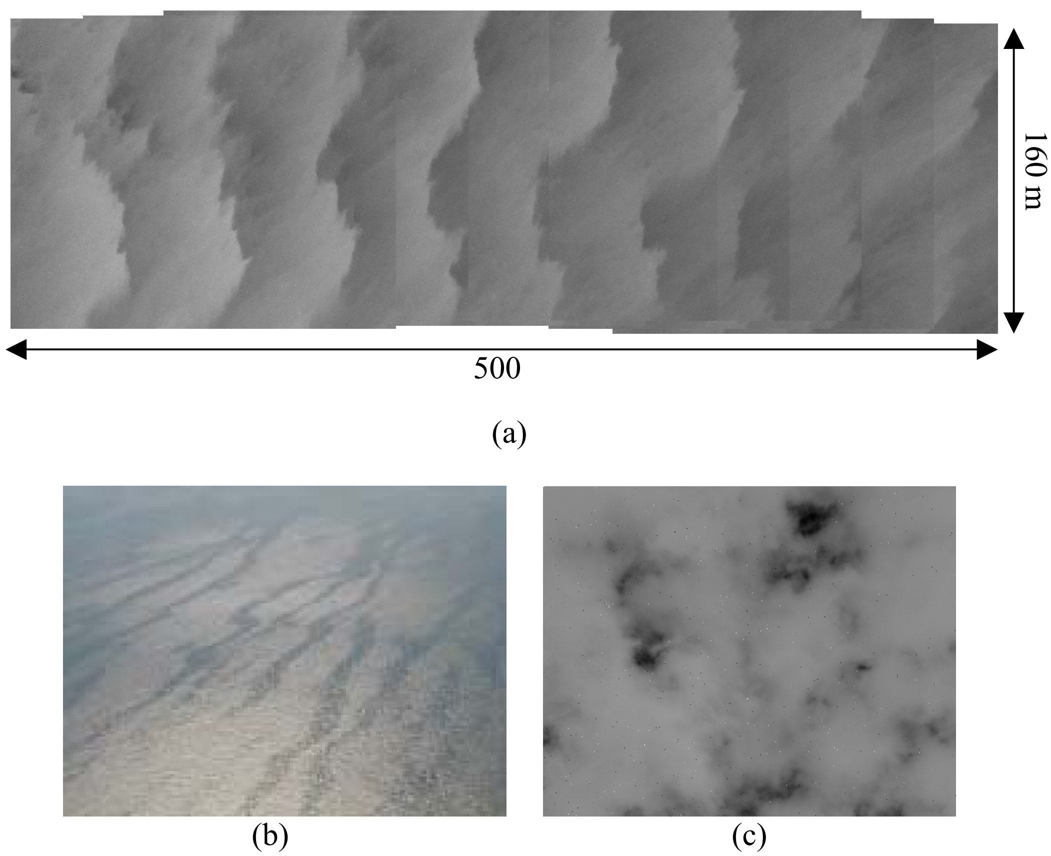


Figure 4. Mosaic of infrared images (a) showing the successive fronts of ocean skin temperature in the presence of ubiquitous surface slicks observed on 8-22-02 during a period when the wind was 5 m s^{-1} from the SW. The top of the mosaic is NE. (b) Picture of the ocean surface slicks observed during the overflight that produced the mosaic in (a). (c) Infrared image of the sky showing that the ocean surface features observed in the downward looking imagery in (a) are, in fact, real temperature structures.

We recently completed the 2nd field campaign over the CBLAST-LOW site in August/September of 2002. We flew our new high spatial resolution dual up- and down-looking longwave IR imaging system from a Cessna Skymaster. Contrary to the pilot experiment, we were able to take useful data during the day since the longwave imager minimized solar contamination of the IR imagery. Similar to last year's pilot study, the IR imagery shows high temperature variability on scales of *O*(10m – 1km). Figure 4a shows a mosaic of IR images that depicts successive temperature fronts in the presence of surface slicks shown in Figure 4b. These data were taken at dawn on 8-22-02 from 2100 - 2230 hours UTC (8-22-02, 1700 – 1830 local) from an altitude of 600 m, which corresponds to a resolution for the imager of roughly 0.3 m. The wind speed was roughly 5 m s^{-1} and the direction was from the SW. An individual IR image is roughly 150 m x 200 m in scale, such that the mosaic is roughly 160 m x 500 m. The low noise level of less than 20 mK is evident in the mosaic in Figure 4a. The variability in temperature across these successive fronts in Figure 4a is of *O*(1-2 ºC) and the spatial scale between the crests of the fronts are of *O*(50 m). The crests of these fronts are parallel to the ubiquitous visible surface slicks shown in Figure 4b. Figure 4c shows an infrared image of the sky simultaneous to the mosaic in Figure 4a. Apparent temperature variability in the IR imagery of the ocean surface may arise on partly cloudy days when both the radiatively-cold sky and radiatively-warm clouds reflect into the imager FOV. The lack of coherent parallel features in the IR sky imagery suggests that the ocean surface features observed in the downward looking imagery in Figure 4a are, in fact, real temperature structures.

IMPACT/APPLICATIONS

The encouraging results of our first two airborne deployments under the CBLAST DRI demonstrate that we will be able to provide sea surface temperature measurements during the main CBLAST experiment in the summer of 2003 with high spatial resolution and accuracy. The impact of our analysis and observations will be to show that remote sensing techniques can quickly characterize the spatial and temporal scales of a wide variety of processes that are important to the air-sea fluxes of heat, mass, and momentum.

TRANSITIONS

None

RELATIONSHIP TO OTHER PROGRAMS OR PROJECTS

This project is in collaboration with A.T. Jessup of the Applied Physics Laboratory at the University of Washington. We are working in closely with R. Weller of WHOI to correlate the IR signatures with environmental conditions measured by the buoys deployed during CBLAST.